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Falcon Research & Development Co
A Subsidiary of Whittaker Corporation
One American Drive
Buffalo, New York 14225
716/632-4932

Whittaker

DEVELOPMENT OF
PARTICULATE EMISSION FACTORS

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Prepared by:

J. C. Bernard

Approved by:

Arthur Stein, Vice President

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The 1977 Clean Air Act amendments require that the Environmental Protection Agency (EPA) set particulate matter standards for motor vehicles and study the effects on health of these emissions. The purpose of this report is to summarize the work done to characterize particulate emissions from mobile sources and to estimate appropriate particulate emission factors.

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TABLE OF CONTENTS

Section	Title	Page
1.0	INTRODUCTION	1
2.0	MEASUREMENT PROCEDURES	3
3.0	NATURE OF PARTICULATE	5
	3.1 Lead Particulate	5
	3.2 Sulfate Particulate	6
	3.3 Diesel Particulate	8
	3.4 Tire Particulate	9
4.0	DISCUSSION OF DATA	10
	4.1 Total Exhaust and Lead Particulate from Noncatalyst Gasoline-Powered Vehicles	10
	4.2 Total Exhaust Particulate from Catalyst Equipped Vehicles	12
	4.3 Total Exhaust Particulate from Diesel-Powered Vehicles	14
	4.4 Sulfate Particulate Emissions from Gasoline and Diesel-Powered Vehicles	16
	4.5 Tire Particulate Emissions	21
	4.6 Total Particulate, Lead and Sulfur Related Emissions from California Vehicles	22
	4.7 Particulate Emissions from High-Altitude Vehicles	22
5.0	PARTICULATE EMISSION FACTORS	26
6.0	REFERENCES	31

LIST OF TABLES

Table	Title	Page
1	Total Exhaust and Lead Particulate Levels from Noncatalyst Gasoline-Powered Vehicles	11
2	Total Exhaust Particulate from Catalyst Equipped Light-Duty Vehicles Measured Over the FTP UDS	13
3	Total Exhaust Particulate Emissions from Diesel-Powered Vehicles	15
4	Sulfate Levels as Measured Over the CFDS and FTP from Gasoline-Powered Vehicles	17
5	Sulfate Levels as Measured Over the CFDS and FTP for Diesel-Powered Vehicles	19
6	Mean Sulfate Levels for Vehicle Technology Types as Measured Over the CFDS	20
7	Particulate Emissions from Light-Duty Gasoline and Diesel-Powered Vehicles at Low and High Altitudes	23
8	Sulfate Levels at Low and High Altitudes Over the CFDS	25
9	Particulate Emission Factors for Low Altitude and California Vehicles	27
10	Particulate Emission Factors for High Altitude Vehicles	29

1.0 INTRODUCTION

The 1977 Clean Air Act amendments require that the Environmental Protection Agency set particulate matter standards for motor vehicles and study the effects on health of these emissions. The purpose of this report is to summarize the work done to characterize particulate emissions from mobile sources and to estimate appropriate particulate emission factors.

The potential health effects from particulate matter are dependent on particle size and chemical composition.[2] Generally, the particle size fraction less than 15 micrometers (μm) is suspendable, inhalable and, if inhaled, deposited to a significant extent in the lower respiratory tract. These small particles (< 15 μm) are typically aggregates, agglomerates or aerosols containing principally carbonaceous, hydrocarbon and sulfate matter in the case of diesel exhaust particulate,. and lead, sulfate and carbonaceous matter in the case of gasoline exhaust particulate.[1,2]

Particulate matter from mobile sources also originates from tire wear. Approximately 55% of the material produced from tire wear results in suspended particulate.[3]

Exhaust particulate emissions have been measured from only a relatively small number of in-use production and prototype vehicles. Both the composition and levels of the exhaust particulate are functions of the type of vehicle engine, composition of the fuel and exhaust system treatment (i.e., catalyst or noncatalyst). For these reasons available measurements and resulting inferred particulate emission factors are presented by relevant technology subgroups for each of the following vehicle types:

- Light-duty passenger vehicles (LDV)
- Light-duty trucks (LDT), GVW* $\leq$ 8500 lbs
- Heavy-duty vehicles (HDV), GVW > 8500 lbs
- Motorcycles (MC)

The above vehicle types have the following technology subgroup classifications, not all of which apply to each vehicle type:

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* GVW = Gross Vehicle Weight

- Noncatalyst using leaded gasoline and 4-stroke engine
- Noncatalyst using leaded gasoline and 2-stroke engine
- Noncatalyst using unleaded gasoline
- Oxidation catalyst vehicles without an air pump*
- Oxidation catalyst vehicles with an air pump*
- 3-way catalyst without an air pump*
- 3-way catalyst with an air pump (i.e., dual bed catalyst)*
- Diesel-powered vehicles using 4-stroke engines
- Diesel-powered vehicles using 2-stroke engines

Particulate emissions may also be characterized by particulate subclass, but it must be remembered that total exhaust particulate as measured over the FTP with a dilution tunnel is the quantity that will be regulated. The subclasses of interest included in this report are lead, sulfate, and tire particulate emissions.

Following some general remarks on measurement procedures and the nature of particulates, in Sections 2 and 3, a review of the available data on particulate emissions is presented in Section 4. This review is organized into five vehicle type/technology/particulate groupings:

- Total exhaust and lead particulate from noncatalyst gasoline vehicles
- Total exhaust particulate from catalyst vehicles
- Total exhaust particulate from diesel vehicles
- Sulfate particulate
- Tire particulate

Finally, in Section 5, emission factors are derived and presented in two summary tables, one for low altitude and California vehicles and the other for high altitude vehicles.

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* Using unleaded gasoline

2.0 MEASUREMENT PROCEDURES

Since the character of particulate emissions changes after combustion due to the physical and chemical processes occurring in the cooler ambient environment, the vehicle's exhaust is ported into a dilution tunnel where it is mixed with a flowing stream of filtered air. The physical (e.g., length, diameter, flow rate) and environmental (e.g., temperature, humidity) characteristics of the dilution tunnel are controlled so that measurements are standardized.[4]

A variety of dilution tunnels exist[1] to measure particulate from gasoline and diesel-powered vehicles. Some tunnels are designed for use with the EPA and SAE steady-state 13-mode heavy-duty truck cycle run on an engine dynamometer and some are designed for use with the FTP car and light-duty truck cycle run on a chassis dynamometer. Total exhaust particulate, which includes lead, sulfate, and carbonaceous matter, depending on vehicle type, is collected and measured by this method.

Measurements are made by inserting an isokinetic* probe into the tunnel and collecting the particulate on a filter of 47 mm diameter. Exhaust particulate is then defined as anything, other than condensed water, that is collected on the filter at a temperature not to exceed 51.7°C (125°F). All the types of particulate resulting from operating the vehicle are trapped in the filter. Total particulate levels are determined by weighing the filters before and after the tests.

Sulfate particulate, considered to be a major portion of the particulate from catalyst equipped vehicles, is measured differently from total exhaust particulate. The sulfate is collected isokinetically on a carbon coated membrane filter in a dilution tunnel as particulate matter. The particulate matter contains hydrated sulfuric acid together with small amounts of sulfate salts (e.g., ammonium sulfate). After the sample is collected, the filter containing the particulate matter is placed in an ammonia atmosphere for a period of time sufficient to convert the hydrated sulfuric acid portion of the particulate to ammonium sulfate. The weight of the filter before the test and after ammoniation gives an estimate of the amount of ammonium sulfate collected.[1,5]

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* Isokinetic sampling can be defined as sampling by drawing a particulate suspension into a probe at the same linear velocity as that of the bulk of the suspension.[1]

The soluble sulfate is then leached from the filter and passed through a column packed with cation exchange resin that scrubs out any interfering halides (e.g., Cl^-, Br^-). The solution is then passed through another cation exchange resin column that converts all the sulfate to sulfuric acid. The sulfuric acid (now minus any interferences) passes through a column of barium chloranilate crystals. The barium exchanges with the H^+ in the H_2SO_4, precipitating out barium sulfate and releasing highly UV absorbing chloranilate ions. The amount of chloranilate ions in solution, which is equivalent to the total amount of $SO_4^=$, is accurately measured by UV spectrometry. The sulfate thus measured includes all the forms of the $SO_4^=$ collected (e.g., H_2SO_4, $(NH_4)_2SO_4$, etc.).

3.0 NATURE OF PARTICULATE

As already discussed, exhaust particulate from mobile sources can be composed of lead, sulfate, and carbonaceous matter depending on vehicle type. In addition, particulate matter from tire wear can make a contribution to the overall impact of particulate on air quality. The nature of each of these types of particulate is discussed.

3.1 Lead Particulate

Exhaust particulate emissions from spark-ignited engines using leaded gasoline is mostly composed of lead compound principally in the form of lead bromochloride (PbBrCl). The exhaust particulate from these vehicles is primarily a function of the amount of lead intentionally added to gasoline and the amount of halogens (i.e., Br and Cl) intentionally added to vaporize the lead. For example, Habibi's[5] determination of total particulate levels from 1966 and 1967 model year passenger vehicles operating on commercial fuel containing 3 grams of lead per gallon showed typical particulate emissions of 350 mg/mi, whereas, measurements of exhaust particulate from a 1974 model year passenger vehicle using gasoline containing 2 grams of lead per gallon showed a typical particulate level of 240 mg/mi.[7]

As a first approximation, lead particulate levels may be estimated by a mass balance approach. Although lead particulate levels are approximately proportional to the amount of lead in gasoline, the amount of particulate and the particle size distributions can vary widely depending on the type of driving cycle, vehicle state of tune and exhaust temperature (all of which are interrelated). Granley and Springer[8] have shown that particle size increase is primarily due to vapor condensation. For example, the less severe the driving cycle (no high accelerations) the lower the exhaust temperature, the larger the particle sizes. Even so, Habibi,[6,9] has shown that 80% of the lead particulate as measured from a passenger vehicle under city-type driving is less than 10 μm in size.

The fraction of total fuel lead exhausted, in general, increases with vehicle speed. The fraction not exhausted is deposited in the combustion chamber, exhaust ports, engine oil and muffler system. Over a driving cycle like the FTP urban cycle about 20-30% of the lead consumed may be exhausted.[10,11] At very high cruise speeds the fraction of lead exhausted may reach 80% or more.[6,10]

3.2 Sulfate Particulate

Sulfate particulate emissions became significant with the introduction of catalyst equipped and diesel vehicles. Sulfate levels from noncatalyst vehicles using leaded and unleaded gasoline are much lower by comparison.

Sulfate emissions in general are proportional to fuel sulfur levels. In the case of vehicles employing diesel technology, sulfate formation is appreciable due to the much higher fuel sulfur content of diesel fuel (0.23% by weight) as compared to the sulfur content of gasoline (0.030% by weight). However, in the case of catalyst equipped vehicles using unleaded gasoline, catalyzed oxidation promotes the formation of increased sulfate.[5,12]

In the combustion process, approximately 99% of the fuel sulfur is converted to sulfur dioxide (SO_2). The sulfur dioxide, in the presence of oxygen and a hot catalytic material such as Pt, is converted into sulfur trioxide (SO_3). In the catalyst where temperatures may range from approximately 700°F* to 1200°F, the SO_3 remains in the gaseous state as SO_3. At the same time the catalyst is oxidizing some of the SO_2 to SO_3, it is oxidizing hydrocarbons (HC) and carbon monoxide (CO) to carbon dioxide (CO_2) and water vapor (H_2O). In fact, the HC and CO have been shown to "be effective competitors with SO_2 for either the catalytic sites or the oxygen, or both," so during periods of "rich engine operation or insufficient oxygen, it follows that less SO_2 will be oxidized."[13]

Also present in the hot exhaust gas in the catalyst are quantities of nitrogen oxides (NO_x), some ammonia (NH_3), and various metals such as iron, zinc, copper, sodium, and manganese. An additional reactant is the alumina substrate of the catalyst. Thus, it is possible that the sulfur oxides react with the trace quantities of metals (which are there because they are present in the gasoline) to form metal sulfates, but it is more likely the metals will oxidize (e.g., to form FeO_2, etc.).[12]

Another interesting phenomenon that occurs in the catalyst is sulfur storage (i.e., not as much sulfur coming out as going in). Gibbs[14] has suggested that the reaction of SO_2, O_2, and the alumina substrate of

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* 700°F to 800°F is approximately the light off temperature of the catalyst when oxidation starts.

the catalyst is the probable mechanism for sulfur storage, considering the low conversions of SO_2 to sulfate and the corresponding high sulfur storage observed.

The hot gases, after leaving the catalyst, begin to cool. The cooling and the particulate formation take place in the ambient environment. Thus the dilution tunnel previously described is necessary to simulate particulate formation. The gaseous SO_3 reacts with water vapor at temperatures less than 644°F to form sulfuric acid (H_2SO_4).[1] The H_2SO_4, being hygroscopic, picks up more water vapor to become hydrated H_2SO_4. This is very much different from diluting H_2SO_4 in water. The hydrated sulfuric acid mist behaves as a particulate.

Since NO_x and NH_3 are present, there are several other possibilities for chemical reactions. NH_3 and the hydrated sulfuric acid may react to form ammonium sulfate particulate (a salt). Also NO_x and NH_3 may form nitric acid (HNO_3) by several reaction schemes, but this is a very slow reaction and probably does not occur in the dilution tunnel. Measurements of nitric acid from vehicles with catalysts show insignificant levels of HNO_3.[15] Also NO_2 may react with SO_2 and H_2O to form H_2SO_4 and NO but this reaction also has a low rate. In fact, all these reactions have slow reaction rates compared to the reaction rate for H_2SO_4 formation and "analysis of the particulate samples taken from catalyst cars showed mostly hydrated sulfuric acid to be present."[5]

Consideration of sulfate is of concern here precisely because it is mostly sulfuric acid aerosol and can potentially affect a very localized area consisting of a high density of catalyst equipped vehicles operating under a congested freeway driving condition. However, mobile source sulfate emissions, and in fact all sulfur emissions, are not significant on a large scale, since they account for less than 1% of the total man-made atmospheric emissions of sulfur compounds which contribute to acid rain.*

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* In the atmospheric photochemical environment the $HC/NO_x/SO_2$ system in combination is a producer of sulfuric acid.[1] In fact, "sulfuric acid is the dominant acid in acid precipitation" whereas "nitric acid appears to contribute about 30 percent."[16]

Although sulfate emissions vary substantially with driving cycle and catalyst technology, the emphasis is placed on circumstances under which sulfuric acid aerosol production from mobile sources could pose a health hazard, specifically, the Congested Freeway Driving Sequence (CFDS). Over the CFDS, approximately 9% of the SO_2 is catalytically oxidized to $SO_4^=$ with 63% exhausted as gaseous SO_2. Over this driving sequence approximately 28% of the SO_2 initially produced in the combustion process is temporarily stored in the catalyst. In addition, the presence or absence of an air pump affects the sulfate levels as measured over the CFDS. Air pump equipped vehicles with catalysts, in general, emit higher levels of sulfate, but the variability in sulfate production is large.

On the other hand, in particular tests over the FTP UDS, essentially all the fuel sulfur is initially oxidized to SO_2. However, 2% is catalytically oxidized to $SO_4^=$, and only 13% of the SO_2 exits the exhaust as gaseous SO_2. The remaining 85% of the SO_2 reacts with O_2 and the alumina substrate of the catalyst, and is temporarily stored. The SO_2 is eventually released when the flow through the catalyst increases and/or the catalyst temperature increases.[14,17] In contrast to the CFDS, there is no measurable difference in sulfate levels between vehicles with and without air pumps as measured over the FTP Urban Driving Sequence (UDS).

3.3 Diesel Particulate

Total diesel exhaust particulate levels are as much as two to four times the total particulate levels from gasoline-powered vehicles using leaded gasoline (i.e., lead particulate), and can be as much as fifty times the particulate levels from gasoline-powered vehicles using unleaded gasoline. Approximately 80% or more of the mass of diesel particulate, which is primarily carbonaceous, is smaller than 1 μm.[1] Thus, most of the diesel particulate is suspended particulate that is inhalable. Further, between 10% and 50% of the exhaust particulate by weight is extractable organic matter.[2] This compares with the exhaust particulate from gasoline-powered light-duty vehicles which is also between 10% and 50% extractable organic matter by weight.[18]

The nature of the carbonaceous matter formed from diesel combustion is variable. The most common form is soot, the major constituent of diesel smoke. The mechanism of sulfate formation in the diesel exhaust is not well understood. However, only a small fraction of fuel sulfur (≈ 2%) is converted to SO_3. The SO_3 forms sulfuric acid particulate in the presence of water vapor.[1]

Diesel particulate is measured as total exhaust particulate from diesel-powered vehicles in a dilution tunnel. No attempt is made to quantify the levels of the constituents of the diesel particulate, except for sulfate.

3.4 Tire Particulate

Particulate levels from mobile sources can arise from vehicle tire wear, as well as from vehicle exhaust. From an estimate of the life expectancy of a tire (e.g., a typical passenger radial might be rated for 40,000 miles) and the weight of the tire tread, tire particulate in grams/mile/tire can be calculated. However, direct measurements of tire wear can be made either in a laboratory or on a test track where the weight loss of a tire can be measured after operation on a simulated roadway for a measured mileage. Also, direct estimates of tire particulate can be made by ambient air sampling in a tunnel or near a roadway.

Of the methods available for tire wear measurement, the method of measuring tire wear rate on a test track is considered the most representative of actual practice. The method of indoor testing of tire wear on a chassis dynamometer, however, gives the best indication of tire particulate size distribution, since tire particulate is most easily collected by this method without interference from other sources.[9]

It is estimated[3] that the largest fraction of tire material lost by wear (90% by weight) is directly transferred to the road surface or is sedimentary particulate. That is, only 10% of the material is initially emitted as suspended particulate. It is, furthermore, estimated that half of the 90% subsequently becomes airborne as suspended particulate. Thus, 45% of the original tire material lost by wear becomes reintroduced into the air stream. Total suspended tire particulate is 10% plus 45% or 55% of the total tire material loss.

Motorcycles and heavy-duty vehicles will produce different levels of tire particulate per vehicle as compared to light-duty vehicles, principally because of the differences in the number of wheels per vehicle and differences in tire life.

One should note that although the calculation described above quantifies the suspended particle fraction of tire wear debris, it does not account for particle size distribution within this fraction. Inasmuch as suspended tire particulates are more heavily concentrated at larger particle sizes than exhaust particulate,[45] a given mass emission rate will tend to produce comparably lower levels of persistent particles. Thus, direct comparisons between tire and exhaust emission factors are not appropriate.

4.0 DISCUSSION OF DATA

No systematic program of measurement over the full span of mobile sources exists for particulate emissions. Most of the data from available sources emphasizes diesel particulate. Measurements of particulate from catalyst equipped vehicles are also available but these are mostly restricted to sulfate levels. Since sulfate particulate measured over the CFDS is of primary interest, it will be considered separately from total exhaust particulate, which is quantified relative to the FTP UDS. The discussion of available data will be divided into areas that are combinations of particulate type, vehicle type and vehicle technology.

4.1 Total Exhaust and Lead Particulate from Noncatalyst Gasoline-Powered Vehicles

The data for exhaust and lead particulate levels from noncatalyst gasoline-powered vehicles measured over the FTP UDS are presented in Table 1. Exhaust particulate levels from light-duty passenger vehicles without catalysts and using leaded gasoline containing 2.0 grams/gallon Pb or less range between 150 mg/mi to 250mg/mi.[15] Another source cites exhaust particulate levels from all non-catalyst light-duty gasoline-powered vehicles ranging from 2 mg/mi to 250 mg/mi.[19] The lead content of the gasoline used in these vehicles is not stated but presumably ranges from less than 0.050 grams/gallon (i.e., unleaded gasoline) to 2.0 grams/gallon.[10,11]

Investigations of the exhaust particulate from vehicles using leaded gasoline by Mueller, et al.,[20] Ter Haar, et al.,[21] Habibi, et al.,[6] and Ninomiya, et al.[22] show that the lead content of the particulate varies between 20-80% by weight. Cadle has shown about 30% Pb in exhaust particulate from one LDV.[15]

Measurements of exhaust particulate from four noncatalyst light-duty vehicles using unleaded gasoline (i.e., less than 0.050 grams/gallon Pb) have been found to range from 26 mg/mi to 50 mg/mi.[15,23] The average exhaust particulate from these four vehicles is 31.5 mg/mi. Because of the small quantities of lead in unleaded gasoline, the lead particulate from these vehicles is presumably only a small fraction of the total particulate.

Table 1

TOTAL EXHAUST AND LEAD PARTICULATE LEVELS FROM
NONCATALYST GASOLINE-POWERED VEHICLES

VEHICLE TYPE	TOTAL EXHAUST* (mg/mi)	LEAD*		FUEL LEAD CONTENT (grams/gallon)
		% by wt.	mg/mi	
LDGV (Several Tests)[19]	2-250	-	-	-
LDGV--Typical LDV's[15]	150-250	25-60%	-	-
"A Typical Vehicle"[15]	250	-	80	-
LDGV 1966 and 1967[6,7]	350	-	280	3.0
LDGVs[6,20,21,22]	-	20-80%	-	-
LDGV 1974 Plymouth[7]	240	33%	-	2.0
LDGV 1974 GM[15]	31	-	-	< 0.05
LDGV 1973 GM[15]	26	-	-	< 0.05
LDGV GM + Air[15]	19	-	-	< 0.05
LDGV 1977 AMC[23]	50	-	-	< 0.05
HDGV (Several Tests)[19]	7-900**	-	-	-
HDGV GM 366[24]	335***	-	-	1.6
MC - 4-Stroke[25]	46	-	-	-
2-Stroke[25]	330	-	-	-

* Measured over the FTP UDS, unless otherwise specified.

** Unknown test cycle.

*** FTP Engine Dynamometer 13 Mode Cycle.

No FTP UDS measurements of exhaust particulate from noncatalyst light-duty trucks using leaded and unleaded gasoline could be found. The exhaust particulate from these vehicle types will be assumed to be the same as from LDV's.

Estimates of exhaust particulate from noncatalyst heavy-duty gasoline-powered vehicles range from 7 mg/mi to 900 mg/mi.[19] A test of one heavy-duty gasoline engine on an engine dynamometer using leaded gasoline with 1.6 grams/gallon Pb resulted in an exhaust particulate level of 558 mg of particulate/kg of fuel as measured over the 13 mode FTP cycle. This is equivalent to 335 mg/mi of exhaust particulate.*

Measurements of exhaust particulate from motorcycles (MC) are also presented in Table 1.

4.2 Total Exhaust Particulate from Catalyst Equipped Vehicles

Total exhaust particulate levels from catalyst equipped vehicles as measured over the FTP urban schedule are presented in Table 2. Total exhaust particulate from catalyst equipped LDV's has been reported in the range of 6 mg/mi to 15 mg/mi.[19] The results of Cadle, et al.,[15] Urban, et al.[22,25] and Springer[24] presented in Table 2 show total exhaust particulate to range from 8 mg/mi[24] to 16 mg.[25] No data exists on the possible effect of mileage on total exhaust particulate, so none will be assumed.

No data exists on total exhaust particulate from light-duty trucks equipped with catalysts. Total exhaust particulate from LDGT equipped with catalysts are assumed equivalent to exhaust particulate from LDGV with catalysts. No heavy-duty gasoline-powered vehicles are equipped with catalysts.

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* $\text{mg/kg fuel} \times 0.454 \text{ kg/lb} \times \frac{A\left(\frac{\text{pounds-fuel}}{\text{gallon}}\right)}{B \text{ (mi/gallon)}} = \text{mg/mile}$

A = Pounds per gallon of fuel = 7.09 (Diesel), 6.08 (Gasoline)

B = 4.6 miles per gallon average fuel economy for both gasoline and diesel heavy-duty vehicles.[43]

Table 2

TOTAL EXHAUST PARTICULATE FROM
CATALYST EQUIPPED LIGHT-DUTY VEHICLES
MEASURED OVER THE FTP UDS

VEHICLE/TECHNOLOGY TYPE	MODEL YEAR/MAKE GROUP	N	MEAN TOTAL EXHAUST PARTICULATE (mg/mi)
All Catalyst and LDGV	---	---	6-15[19]
Oxidation Catalyst LDGV	77 GM[15]	2	9
	78 GM and Ford[23]	4	13
	77 GM and VW[24]	2	8
3-Way Catalyst LDGV	78 GM[15]	2	11
	78 and 79 GM, Ford and SAAB[26]	4	16

4.3 Total Exhaust Particulate From Diesel-Powered Vehicles

Total exhaust particulate from light-duty diesel vehicles (LDDV) are grouped by make/model because of the differences in exhaust particulate levels among VW, GM, and Mercedes/Peugeot, as may be noted in Table 3.[24,27-30] LDDV's did not become a significant fraction of the in-use light-duty vehicle fleet until the 1977 model year.[2] Previously, most diesel passenger vehicles were of foreign manufacture (e.g., Mercedes and Peugeot). Light duty diesel-powered passenger vehicles from the 1977 through 1980 model years are dominated by the GM and VW diesel (approximately half GM and half VW). The pooled averages of the exhaust particulate from the groups: GM, VW and Mercedes/Peugeot from Table 3 are 845 mg/mi, 338 mg/mi, 479 mg/mi, respectively. Thus prior to 1977, exhaust particulate levels are about 479 mg/mi. After 1977, average exhaust particulate levels are about 592 mg/mi (i.e., half GM and half VW particulate).

Mileage accumulation effects on exhaust particulate emissions have been shown by Gibbs[29] to be nonsystematic (i.e., no discernable trend with mileage). Further, White, et al,[30] have demonstrated negligible changes in particulate emissions over an average 48,000 miles. Thus, no mileage effects on diesel exhaust particulate are assumed.

Total exhaust particulate emissions from light and heavy duty diesel trucks are also presented in Table 3. It should be noted that the measured exhaust particulate levels from the four LDDT's presented are equivalent in magnitude to levels from LDDV's even though there is a demonstrably consistent relationship between vehicle weight and exhaust particulate emissions[2] (estimated at 20% increase in particulate per 1000 lb increase in inertia weight).[24,27,31-34]

Exhaust particulate emissions from HDDV's presented in Table 3 are measured on an engine dynamometer over the 13 mode and transient cycles. Exhaust particulate emissions as measured over the transient cycle on a chassis dynamometer as reported by Dietzmann are also presented.[29] In all cases, the exhaust particulate levels reported in Table 3 are from HDDV using diesel fuel number 2 with 0.23% by weight sulfur. The 2-stroke diesel particulate levels reported are levels characteristic of a city bus.

Starting in model year 1982 all light-duty diesel-powered passenger vehicles and trucks will be required to meet exhaust particulate standards of 600 mg/mi.[2] By the 1985 model year exhaust particulate standards will be reduced to 200 mg/mi for light-duty diesel powered passenger vehicles and 260 mg/mi for light-duty diesel-powered trucks.

Table 3

TOTAL EXHAUST PARTICULATE EMISSIONS FROM DIESEL-POWERED VEHICLES

Vehicle/Technology Type	Model Year/Make	No. of Vehicles	Mean Total Exhaust Particulate (mg/mi) ± 1 std. dev.
LDDV††	74 Mercedes-Peugeot[27]	4	449
	75 Mercedes[28]	1	442
	79 Certification Mercedes/Peugeot[2]	4	520
	81 Prototype Mercedes/Peugeot[2]	4	415
	77, 78, 79 Mercedes, Peugeot, Audi[29]	6	523 ± 79
	79, 80 Olds, Cad.[29]	7	840 ± 108
	Olds[30]	20	850 ± 164
	77, 78, 79 VW[29]	5	370 ± 52
	78, 79 GM[15]	4	813
	77 GM[24]	1	920
	77 VW[24]	1	290
	79 Cert. VW[2]	2	280
LDDT††	75 Perkins[27]	1	742
	79 Certification Nissan, GM, Mitsubishi[2]	3	530†††
HDDV 4-Stroke	76-80 Caterpillar, Cummins, Detroit DA, Deutz, Mack[31]	14	1489 ± 490*
	Caterpillar[32]	1	1970†
	Mack[24]	1	2440†
	Cummins Turbo[33]	1	997†
	Cat., Mack, Cummins[34]	3	1487**
HDDV 2-Stroke	DDA, Cummins[31]	3	1430*
	DDA[32]	1	4540†
	DDA[33]	2	2381†
	DDA[34]	1	3330**

* Measured over Transient Cycle on engine dynamometer.

** Measured over Transient Cycle on chassis dynamometer.

† Measured over 13 mode FTP on engine dynamometer.

†† Measured over FTP UDS.

††† These are certification type FTP tests as LDDTs do not currently certify for particulate emissions.

4.4 Sulfate Particulate Emissions From Gasoline and Diesel-Powered Vehicles

Mean sulfate levels from gasoline-powered vehicles are presented in Table 4. Sulfate levels from noncatalyst light-duty vehicles using both leaded and unleaded gasoline have been found to be low, generally less than 1.0 mg/mi. However, Somers, et al.,[5] have found individual levels as high as 2 mg/mi. In any case, the sulfate levels from noncatalyst vehicles are relatively low and stable, i.e., are not as sensitive to driving cycle (e.g., FTP urban or CFDS) and technology (e.g., air pump) as light-duty sulfate levels from catalyst equipped vehicles. Note from Table 4 that the sulfate level from one noncatalyst HDV is of the same magnitude as from LDV's. Sulfate levels from catalyst equipped light-duty vehicles vary widely, a fact that is especially evident when sulfate is measured over the CFDS. As a point of note, sulfate levels considered only over the FTP urban cycle are lower and less variable by comparison.

Other factors that affect sulfate levels from catalyst vehicles are catalyst type (i.e., monolith or pelleted) and the presence or absence of an air pump. Somers, et al.,[5] Gibbs, et al.,[15] and Herling, et al,[17] have all noted somewhat higher sulfate emissions from catalyst LDV's that are also equipped with air pumps. However, accompanying the increase in the average magnitude of sulfate levels is in general a corresponding increase in the variability from vehicle to vehicle. For instance, the mean sulfate levels of 23 light-duty vehicles equipped with oxidation catalysts and air pumps as measured by Somers, et al., was 28 mg/mi.[5] The standard deviation of the group was 25 mg/mi. The mean sulfate levels of 13 light-duty vehicles equipped with oxidation catalysts and without air pumps as measured by Somers, et al., was 9 mg/mi with a standard deviation of 11 mg/mi.[5] Comparable levels of variability have also been noted by Herling, et al.[17]

With these large levels of variability, the hypothesis that the means of the two groups (i.e., catalysts with air and catalysts without air) are different would not be accepted under good statistical practice. This does not imply that the sulfate levels for the two technology groups are the same, but only that the difference cannot be demonstrated with the available data. There are perhaps other factors such as catalyst type and state of maintenance of the vehicle (e.g., vehicle operated in a rich condition) that could serve as explanatory variables to reduce variability. For instance, Somers[5] notes that a vehicle equipped with an oxidation catalyst but without an air pump in a lean state of tune can produce very high sulfates comparable to levels from catalyst vehicles with air pumps. Similarly, a catalyst and air pump vehicle operating in a very rich condition can produce very low sulfate. In fact, White[35] has shown that approximately half of all in-use vehicles operate at a rich (relative to specifications) idle-mixture that is mostly responsible for the high carbon monoxide (CO) levels from vehicles. Gibbs[15] has further noted

Table 4

SULFATE LEVELS AS MEASURED OVER THE CFDS AND FTP FROM GASOLINE-POWERED VEHICLES

Technology/Vehicle Type	No. of Vehicles	Sulfate		Mean SO_2 (mg/mi)
		CFDS (mg/mi) Mean ± 1 Std. Dev.	FTP (mg/mi) Mean	
Noncatalyst LDV Using Leaded Gasoline	2[15]		1.0	
	1[5]	0.2	---	
Noncatalyst LDV Using Unleaded Gasoline	4[15,23]	1.0	1.0	130
	2[5]	1.7	---	
Noncatalyst HDV Using Leaded Gasoline	1[24]	---	1.4***	
Oxidation Catalyst Unleaded With Air Pump	2[23]	5.6*	2.0	
	81[17]	16.8* ± ≈16	---	
	11[14]	15.0*	---	
	25[5]	28* ± 25	---	
	26[35]	25.0	---	
Oxidation Catalyst Unleaded With No Air Pump	2[23]	0.4	0.9	
	2[24]	11.2	1.2	
	15[17]	4.8 ± 4	---	
	38[14]	3.0	---	
	13[5]†	8.8 ± 11	---	
3-Way Catalyst Unleaded With Air (Dual Bed)	1[15]	---	1.7	
	2[26]	6.3	3.3	
	6[5]	33.8	---	
	4[36]	20.0		
3-Way Catalyst Unleaded With No Air	2[26]	0.2	0.4	
	2[5]	1.2	---	

* Normalized to 0.03% wt. sulfur in fuel.

** UDS unless otherwise specified.

*** 13 Mode Cycle.

† Excludes one outlier vehicle.

that sulfate levels are, in general, inversely proportional to CO. Thus, the high CO levels measured from in-use vehicles partially explain the low sulfate levels measured from in-use vehicles.

Related to the question of sulfate and CO dependency and the effects of maintenance on those quantities is the question of mileage dependence. Tests by the manufacturers of the effects on sulfate levels from catalyst equipped vehicles due to mileage show no conclusive results. The sulfate levels, as noted by Hummel,[36] exhibited much variability. Most of the vehicles were equipped with air pumps. The average sulfate from these vehicles was approximately 25 mg/mi. The sulfate levels from four dual bed catalysts (i.e., 3-way catalysts equipped with air pumps) were approximately 20 mg/mi. This is consistent with the levels presented in Table 4 of 34 mg/mi from Somers, et al.,[5] and of 6 mg/mi from Urban, et al.[26]

In catalyst equipped LDV's, no statistically supportable difference between the sulfate levels from vehicles with air as compared to the vehicles without air can be demonstrated. However, measured sulfate levels from air-pump-equipped vehicles were on the average higher than levels from vehicles without air. Thus, in the interests of assessing the potential impacts of sulfate in those areas where large numbers of catalyst vehicles equipped with air pumps operate, sulfate levels will be disaggregated into the groups with and without air.

The sulfate levels from diesel powered vehicles are presented in Table 5. It may be noted that sulfate levels are insensitive to driving cycle. The average levels for different vehicle technology types are computed from Table 5 and are presented in Table 6, along with the mean sulfate levels from catalyst vehicles from Table 4.

It should be noted that the sulfate levels for gasoline-powered vehicles in Table 4 have been normalized to the national average fuel sulfur content of 0.03% by weight. Also the sulfate measurements from diesel vehicles in Table 5 used fuel with a sulfur content of 0.23% by weight except for the one case as noted.

Since sulfur emissions have been shown to be generally a linear function of fuel sulfur content,[13] sulfur emissions (e.g., as SO_2 or $SO_4^=$) can be determined by a mass balance approach. Specifically sulfur emissions can be estimated from fuel economy (miles/gallon), fuel density (grams/gallon) and sulfur content of the appropriate fuel (weight percent). Since most of the fuel sulfur is initially converted to SO_2 by the combustion process, SO_2 is calculated by the relation:

$$SO_2 \text{ (mg/mi)} = \frac{(2)\ (\text{wt. \% S})\ (\text{density (mg/gal)})}{\text{F.E. (gal/mi)}}$$

Table 5

SULFATE LEVELS AS MEASURED OVER THE CFDS AND FTP
FOR DIESEL-POWERED VEHICLES

Technology/Vehicle Type	No. of Vehicles	Mean Sulfate* CFDS (mg/mi)	Mean Sulfate* FTP (mg/mi)	Mean SO_2 (mg/mi)
LDDV	6[5]	10.5	--	
	4[27]	11.8	12.2	499
	2[24]	12.0	11.0	
	4[15]	--	12.5	899
LDDT	1[27]	18.0	18.0	
HDDV 4-Stroke	1[32]	--	77.0	
	2[24]	--	93.0	
	2[33]	--	70.0	
HDDV 2-Stroke	1[32]	--	69.0	
	1[33]	--	118.0	

* Normalized to 0.23 wt % fuel sulfur.

The factor 2 is the ratio of the molecular weight of SO_2 to S. As an example, a GM diesel vehicle getting 21 mpg[30] and using diesel fuel with 0.23% by weight sulfur, would produce 703 mg/mi of SO_2. This compares with the average measured value of 899 mg/mi by Cadle[15] in Table 5.

Table 6

MEAN SULFATE LEVELS FOR VEHICLE TECHNOLOGY TYPES AS MEASURED OVER THE CFDS

Vehicle/Technology Type	Sulfate Particulate CFDS (mg/mi)
Noncatalyst LDGV[5,15,23]	1
Noncatalyst HDV[24]	1
Oxidation Catalyst LDV With Air Pump[5,14,17,23,36]	20
Oxidation Catalyst LDV Without Air Pump[5,14,17,23,24]	6
3-Way Catalyst LDV With Air Pump[5,15,26,36]	25
3-Way Catalyst LDV Without Air Pump[5,26]	1
LDDV[5,15,24,27]	11
LDDT[27]	18
HDDV (4-Stroke)[24,32,33]	81
HDDV (2-Stroke)[32,33]	94

4.5 Tire Particulate Emissions

A review of the subject of particulate emissions from tire wear has been conducted by Carvitti.[3] In this review, the most representative tire particulate wear rate was found to be 0.34 gm/vehicle-mile, obtained from tests conducted by Veith[37] on light-duty passenger vehicles. The implied per-tire wear rate is 0.085 gm/mile/tire.

No direct measurements of tire wear from heavy-duty vehicles exist. However, from data collected from the monitoring of 20 truck fleets,[38] average tread removal at tire end life is 13/32 inches. Considering a typical 3-rib truck tire, this represents 14.75 lbs or 6700 gm of material worn from the average truck tire during its useful life. Also, tire life or mileage depends on tire type (e.g., bias belted or radial) and tire function (e.g., steering, traction, trailer). A truck tire's useful life can range from 75,000 to 140,000 miles depending on tire type/function. Thus, the wear rate of a truck tire can span the range of 0.042 gm/mile/tire to 0.084 gm/mile/tire. This is compared with the average wear rate of 0.085 gm/mile/tire from LDV's and, due to lack of additional information, the wear rate for LDV's will also be applied to HDV's.

According to Wards Automotive Yearbook, the average HDV has 8 tires.[39] This gives a total wear rate of 0.68 gm/HDV-mile.

The tire wear rate from motorcycles (MC), due to lack of data, is estimated to be equivalent to tire particulate from LDV's. For the two-wheeled motorcycle, this results in an estimate of 0.17 gm/MC-mile.

The total airborne particulate from mobile sources has been estimated to be 55% of the tire material produced from wear (i.e., 10% initially airborne from tire wear plus 45% reentrained particulate).[3] Application of this factor produces the total suspended tire particulate emission factors of 190 mg/LDV-mile, 370 mg/HDV-mile, and 94 mg/MC-mile.

4.6 Total Particulate, Lead and Sulfur Related Emissions from California Vehicles

There are no data available to suggest that total particulate, lead and sulfur related emissions from California vehicles are different from those of 49-states' vehicles by vehicle type/subgroup. However, it is well-known that the technology subgroup mix in California is different from the 49-state technology mix due to the different standards in California for the regulated emissions HC, CO, and NO_x. Consequently, the composite emission inventories (the total emissions loadings due to the sum of all vehicle types/subgroups) for total particulate, lead and sulfur related emissions are somewhat different in California as compared to the 49 states.

The emission results presented in previous sections by vehicle type/subgroup are therefore presumed also valid for California vehicles. Only the vehicle type/subgroup proportions are different.

4.7 Particulate Emissions from High-Altitude Vehicles

Most of the data on the effect of altitude on exhaust particulate emissions are from diesel-powered light-duty vehicles. Table 7 presents the results of testing the same nine LDDV's at both low and high altitudes.[40,41] It is important that the same vehicles are tested at the two locations in exactly the same way using the same fuel.* One should also attempt to rule out other possible systematic biases, e.g., due to differences between test facilities. Only in this way can any statistically significant observed differences in the measured exhaust particulate levels be attributed to an altitude effect.

Included in Table 7 are the percent increases or decreases calculated according to the relation

$$\left(\frac{\text{Particulate at Denver}}{\text{Particulate at Low Altitude}} - 1\right) \times 100\%$$

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* Altitude compensation modifications to reflect real differences in production vehicles sold at high altitudes should, however, be made.

Table 7

PARTICULATE EMISSIONS FROM LIGHT-DUTY
GASOLINE AND DIESEL-POWERED VEHICLES
AT LOW AND HIGH ALTITUDES

VEHICLE TYPE	EXHAUST PARTICULATE OVER FTP URBAN CYCLE		
	LOW ALTITUDE (mg/mi)	DENVER (mg/mi)	PERCENT CHANGE
LDDV - 1980 VW[40]	260	400	54%
1979 Olds[40]	780	980	26%
1979 Olds[40]	1130	1820	61%
1974 Peugeot*[40]	2430	2430	0%
1977 Mercedes 240D[40]	360	470	30%
1978-1979 Experimental GM[41]	790	650	-18%
1978-1979 Experimental GM[41]	500	800	60%
1978-1979 Experimental GM[41]	330	640	94%
1978-1979 Experimental GM[41]	440	620	41%
			39% ± 34%**
LDGV - Precatalyst GM[18]	62	76	23%
Catalyst GM[18]	14	13	-7%

* This vehicle was considered to be improperly maintained.

** Mean ± 1 Standard Deviation; the mean can be shown to be statistically different from zero.

for each vehicle. Since there are so few vehicles tested, the average percent change in exhaust particulate due to altitude is a better measure of the altitude effect than the measured magnitude of the exhaust particulate at Denver. That is, an average of the exhaust particulate levels of a group of vehicles in Denver would not be a representative measure of exhaust particulate at high altitude unless the group were large enough to represent a typical sample of Denver vehicles. Of course, we have tacitly assumed that the low altitude sample is a representative sample.

The average percent change in exhaust particulate due to altitude for the LDDV's in Table 7 is a statistically significant 39% increase at Denver from the low altitude levels. Since no other information is available, this factor will be applied to all exhaust particulate from diesel-powered vehicles at low altitude to estimate exhaust particulate at high altitude.

Also included in Table 7 is the effect of altitude on exhaust particulate from two gasoline-powered vehicles, one precatalyst and one catalyst vehicle.[18] The results, as shown, were mixed. Furthermore, there was no indication of recalibration for altitude compensation in these two vehicles. The same study[18] included comparison of results on separate sets of precatalyst and catalyst LDGV's native to low altitude environment and Denver, respectively. The comparison showed a 30% average increase in total particulate at high altitudes. However, the small sample size and the question of comparability under high vehicle-to-vehicle variability make these data inconclusive.

Sulfate emissions from LDGV's at high and low altitudes have been reported by Liljedahl, et al.[42] as measured over the CFDS. These results are reproduced in Table 8 and show sulfate levels to be somewhat lower in Denver as compared to Houston and Phoenix. This result is consistent with the fact that CO levels in Denver are much higher compared to low altitude. The higher CO, coupled with the fact that sulfate levels tend to vary inversely with CO levels,[15] may explain the low sulfate levels in Denver. The ratio of the mean sulfate in Denver to the overall (i.e., pooled) mean level for Houston and Phoenix is computed to be 0.32. Thus, sulfate levels in Denver are 68% lower than sulfate levels at low altitude. With the sample estimates of the standard deviations in Table 8, it can be demonstrated that the sulfate levels in Denver are statistically lower than the levels in Phoenix and Houston.

Tire particulate levels representative of high altitudes are not available. Based on engineering judgment of the mechanisms involved, tire particulate at low and high altitudes are assumed equivalent.

Table 8

SULFATE LEVELS AT LOW AND HIGH ALTITUDES OVER THE CFDS[42]

LOCATION	NO. OF VEHICLES	SULFATE (mg/mi)	
		MEAN	STANDARD DEVIATION
Denver	66	2.22	3.18
Houston	64	5.77	10.18
Phoenix	155	7.43	21.61

5.0 PARTICULATE EMISSION FACTORS

The particulate emission factors for total exhaust, lead, sulfate, and tire particulate are presented in Table 9 for all low altitude and California vehicle/technology types. Similarly, the particulate emission factors for high altitude vehicle/technology types are presented in Table 10.

In all cases where applicable, total exhaust particulate from non-catalyst vehicles using leaded gasoline is normalized to 2.0 grams/gallon Pb. Further, taking an intermediate value from experimental data in Table 1, we assume lead particulate to be 30% of total exhaust particulate as measured over the FTP urban cycle from noncatalyst vehicles using leaded gasoline. This assumption is order-of-magnitude consistent with calculations based on fuel lead content, vehicle fuel economy and percent total lead emitted as particulate.

No information is available on total exhaust particulate from HDGV using unleaded gasoline. Since exhaust particulate from this vehicle/technology configuration is expected to be significant, the emission factor is estimated by the following:

$$\text{Total Exhaust}_{\text{HDGV(Unleaded)}} = \frac{\text{Total Exhaust}_{\text{LDV(unleaded)}}}{\text{Total Exhaust}_{\text{LDV(leaded)}}} \left(\text{Total Exhaust}_{\text{HDV(Leaded)}}\right)$$

$$= \frac{32}{240}\,(420) = 56 \text{ mg/mile}$$

No measured data could be found on total exhaust, lead, sulfate, and tire particulate emissions from light-duty gasoline-powered trucks, (LDGT). Based on engineering judgement that the differential in average weight and average fuel economy between LDGT's and LDGV's is relatively minor[44] and that thetwo vehicle classes are similar within individual technology subgroups, LDGT emission factors are assumed equivalent to LDGV's.

For light-duty diesel-powered trucks (LDDT), the little data available indicate no difference in exhaust particulate levels between LDDT's and LDDV's. On the other hand, test simulations have shown that diesel exhaust particulate levels are a function of vehicle inertia weight, with exhaust particulate increasing 20% per 1000 lb. increase in vehicle inertia weight. The data in Table 3 do not confirm this difference and, furthermore, exhaust particulate standards for LDDV's and LDDT's to be imposed on 1982 through 1984 model years are identical and roughly equivalent to currently measured levels. It is

Table 9

PARTICULATE EMISSION FACTORS FOR LOW ALTITUDE AND CALIFORNIA VEHICLES

Vehicle Type	Technology Type	Total Exhaust FTP (mg/mile)	Lead FTP (mg/mile)	Sulfate CFDS (mg/mile)	Tire (mg/mile)
LDGV/T	Noncat. Leaded	240[a]	72[l]	1[p]	190[z]
LDGV/T	Noncat. Unleaded	32[b]	2[m]	1[p]	190
LDGV/T	Ox. Cat, No Air Pump	11[c]	0[n]	5[q]	190
LDGV/T	Ox. Cat, Air Pump	11[c]	0	20[r]	190
LDGV/T	3W Cat, No Air Pump	14[d]	0	1[s]	190
LDGV/T	3W + Ox. Cat, Air Pump	14[d]	0	25[t]	190
HDGV	Noncat. Leaded	420[e]	130[l]	1[u]	370[aa]
HDGV	Noncat. Unleaded	56[f]	4[m]	1[u]	370
LDDV	All	600[g]/200[h]	0[o]	11[v]	190
LDDV	All	600[g]/200[h]	0	18[w]	190
HDDV	2-Stroke	2400[i]	0	94[x]	370
HDDV	4-Stroke	1500[j]	0	81[y]	370
MC	2-Stroke	330[k]	-	-	94[bb]
MC	4-Stroke	46[k]	14[l]	-	94

- Denotes no available basis for estimate.

(a) Typical 1974 LDV using gasoline with 2.0 grams/gal Pb.[6,7,15]

(b) 4 vehicles.[15,23]

(Footnotes (c)-(bb), Continued on next page)

Table 9

Footnotes (Continued)

(c) 6 vehicles.[15,23,24]

(d) 6 vehicles.[15,26]

(e) 1 vehicle[24] normalized to 2.0 gm/gal leaded gasoline.

(f) Indirect estimates from LDGV/T and HDGV (leaded gas) factors.

(g) Particulate emission standards for 1982-1984 Model Years.

(h) Particulate emission standards for 1985 and later Model Years.

(i) 7 vehicles.[31,34]

(j) 20 vehicles.[24,31-34]

(k) (See Ref. 25).

(l) Indirect estimate from total particulate factor and assumed 30% lead fraction.[6,7,15,20]

(m) Indirect estimate from leaded gasoline factor and ratio of lead content, unleaded to leaded gasoline.

(n) Assumes all lead deposited in catalyst.

(o) Assumes no significant lead levels in diesel fuel.

(p) 7 vehicles.[5,15,23] (Combines leaded and unleaded gasoline usage)

(q) 70 vehicles.[5,14,17,23,24]

(r) 145 vehicles.[5,14,17,23,35]

(s) 4 vehicles.[5,26]

(t) 12 vehicles.[5,26,36]

(u) 1 vehicle.[24] (assumed applicable to both leaded and unleaded gasoline usage)

(v) 12 vehicles.[5,24,27]

(w) 1 vehicle.[27]

(x) 2 vehicles.[32,33]

(y) 5 vehicles.[32,33,34]

(z) Based on representative wear rate[3] x 55% suspension factor.

(aa) Based on LDV factor per tire and average of 8 tires per HDV.[39]

(bb) Based on LDV factor per tire and 2 tires per MC.

Table 10

PARTICULATE EMISSION FACTORS FOR HIGH ALTITUDE VEHICLES[a]

VEHICLE TYPE	TECHNOLOGY TYPE	TOTAL EXHAUST FTP (mg/mile)	LEAD FTP (mg/mile)	SULFATE CDFS[c] (mg/mile)	TIRE (mg/mile)
LDGV	Noncat. Leaded	240	72	0	190
	Noncat. Unleaded	32	2	0	190
LDGV1	Ox. Cat., No Air Pump	11	0	2	190
LDGV2	Ox. Cat., Air Pump	11	0	6	190
	3W Cat., No Air Pump	14	0	0	190
	3W + Ox. Cat., Air Pump	14	0	8	190
HDGV	Noncat. Leaded	420	130	0	370
	Noncat. Unleaded	56	4	0	370
LDDV	All	830/280[b]	0	4	190
LDDT	All	830/360[b]	0	6	190
HDDV	2-Stroke	3400[b]	0	30	370
	4-Stroke	2100[b]	0	26	370
MC	2-Stroke	330	-	-	94
	4-Stroke	46	14	-	94

- Denotes no available bases for estimate.

(a) All factors equivalent to low altitude factors unless otherwise noted.

(b) Assumes 39% increase in diesel total particulates relative to low altitudes, based on 9 vehicle tests.[40,41]

(c) Assumes 68% decrease in all sulfate emissions relative to low altitudes, based on 66 high altitude and 219 low altitude tests.[42]

therefore assumed that the standard will be met, and the standard is selected as the appropriate emission factor for all model years through 1984. For 1985 and later model years, it is similarly assumed that the reduced standards for LDDV's and LDDT's will be met, and these are taken as the applicable emission factors.

The tire wear rate of 0.085 grams/mile/tire estimated for LDV's is assumed applicable to all vehicle types due to lack of any other data. Tire particulate is then computed by vehicle type based on the average number of wheels per vehicle and the estimate that 55% of the tire material from tire wear becomes suspended tire particulate.

Total exhaust particulate from all diesel-powered vehicles at high altitude are estimated to increase by 39% over the levels at low altitude. Sulfate levels at high altitude are estimated to decrease by 68% over the levels at low altitude. Due to lack of sufficient data, as previously noted, all other particulate factors at high altitude are assumed equal to low altitude factors.

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